Validation of Cloud Optical Depths Retrieved from EOS/MODIS Data

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Summary

The ultimate goal of this project is to develop some validation tools for the optical thicknesses retrieved from MODIS data at locales where no other in situ measurements are available. We propose a theoretical method that should provide important information on how accurate operational cloud retrievals are. This method will help to better understanding errors related to cloud horizontal inhomogeneity in operational cloud retrievals and set error bounds on the inferred values. The method is based on estimating the effect of photon horizontal fluxes on the retrieval of cloud optical properties and will be validated using microwave radiometer data at two ARM sites (Oklahoma and Western Pacific).

Since the beginning of the funding, our research activity has been directed in the following:

- calculating and accumulating 3D radiance fields for different horizontal distributions of cloud optical depths, cloud top variabilities and surface properties;
- retrieving cloud optical depths from calculated radiances using an operational 1D independent pixel assumption and two newly developed methods that account for 3D radiative effects: "nonlocal" independent pixel approximation and normalized difference between non-absorbing and absorbing wavelengths;
- retrieving cloud optical depth from Landsat data and comparison with ground-based microwave radiometer liquid water path measured at the ARM site in Oklahoma.

We are advancing on all three fronts at once and sometimes integrate two or all three aspects into a single publication. The scientific results of our investigation are reported in 7 peer-reviewed papers and 5 conference proceedings.

We established contact with ASTER instrumental team and submitted a proposal to request for ASTER data. Our request for 15-m spatial resolution ASTER VNIR data of Stratocumulus clouds over the two ARM sites (Oklahoma and Western Pacific) has been approved.

The home page of our validation investigation is at http://climate.gsfc.nasa.gov/~marshak/Validation.html.

Except for travel, Cahalan, Davis, and Wiscombe do not require any funding from this project. Despite of a wide search, we could not find a graduate student suitable to work on this project. Instead, following worldwide advertising, Dr. Tamás Várnai was hired in May 1999. He is an atmospheric physicist who graduated from McGill University, where he studied the reflection of radiation by inhomogeneous clouds (under Prof. Roger Davies, an expert in 3D radiative transfer). Since 1997, Tamás worked as a postdoc at the Institute of Atmospheric Physics, University of Arizona, where he was involved in the development of cloud property retrieval algorithms for the Multi-angle Imaging SpectroRadiometer (MISR).

Overview

(1) 3D radiative effects

Let us first illustrate what we mean by 3D radiative effects. In Fig. 1a we plotted a 5 km fragment of simulated nadir radiance field, as it would be measured by a 25-m resolution satellite. In addition, in Fig. 1b we have a 5 km fragment of a stochastic model of cloud optical depth that corresponds to the radiances from panel (a). We see a strong increase in brightness around cloud edges (3.2 km) and shadows behind them (3.4 km); this is a signature of low-order scatterings. On the other hand, for large optical thicknesses (from 0 to 0.7 km and 4.2 to 4.7 km), we observe smoother behavior of nadir radiances than the corresponding cloud field. This is called “radiative smoothing”—a process that is determined by multiple scattering and photon horizontal transport.

To conclude, there are two competing radiative processes: shadowing (or “roughening”) and smoothing (Marshak et al., 1999b); while the shadowing makes fluctuations larger, the smoothing suppresses them. This is clearly seen in the wavenumber spectra (Fig. 2a): while roughening flattens the spectra (see θ_0=60^o case), smoothing steepens it (see both θ_0=60^o and θ_0=0^o cases). The roughening is more pronounced for intermediate scales while smoothing for small scales. To illustrate that, we added the wavenumber spectrum of a Landsat image taken over the ARM

CART site in Oklahoma (Fig. 2b). Signatures of both 3D radiative processes are clearly seen: smoothing for scales smaller than 0.5-1 km and roughening for scales from 0.25 to 2-3 km.

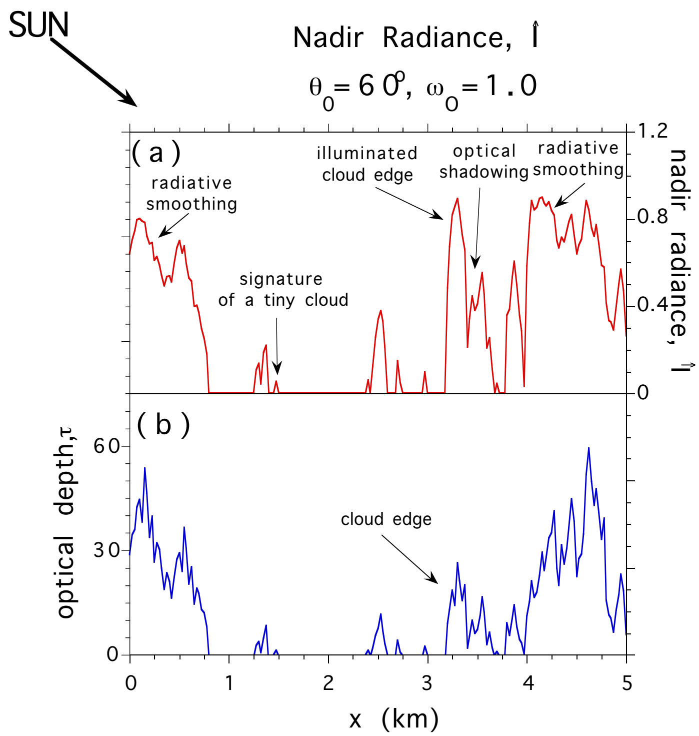

Figure 1: *3D radiative effects*. **(a)** A 5 km fragment of nadir radiance, calculated by a Monte Carlo method. Pixel size is 25 m, solar zenith angle $\theta_0 = 60^o$ (illumination from the left), conservative scattering, Henyey-Greenstein scattering phase function, "black" surface. **(b)** A 5 km fragment of horizontal distribution of optical thickness, that corresponds to the zenith radiance plotted in panel (a). Geometrical cloud thickness is 300 m.

All these 3D radiative effects violate a one-to-one relationship between optical depth and nadir radiances and in many cases make it impossible to retrieve cloud optical thicknesses at a pixel-by-pixel basis. In some cases, the one-to-one relationship is not restored even after substantial averaging. Figure 3a illustrates this with a scatter plot of averaged over 800 m (32 points) nadir radiances calculated by the Monte Carlo method for 10 realizations of a stochastic cloud model plotted vs. cloud optical depth.

(2) Approaches for validating cloud optical depth retrieval.

There are two approaches we have been pursuing to estimate the effect of these two 3D radiative processes on cloud optical depth retrieval.

(2a) Small scales. For small scales, we apply the Nonlocal Independent Pixel Approximation (NIPA) developed by us and reported in Marshak et al. (1998a). This method restores the optical

depth variability that would be underestimated by an operational Independent Pixel Approximation (IPA) technique. For pixel-by-pixel retrievals of cloud optical depth, both IPA and NIPA are applied to all simulated radiance data (for an example, see a 5-km fragment in Fig. 3b). As expected, NIPA sharpens the radiatively smoothed field of retrieved optical depths by generating small-scale structure similar to the original optical depth field.

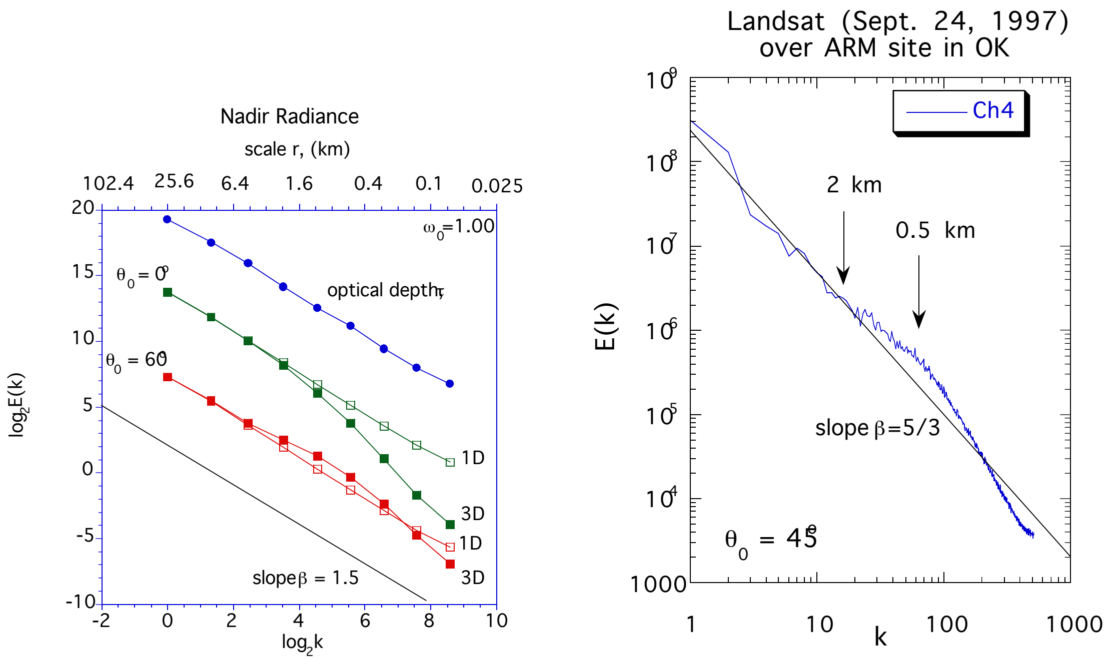

Figure 2: *Wavenumber spectra.* **(a)** 10 realizations of cloud optical depths (above) and zenith radiances (below) calculated using 1D and 3D radiative transfer for $\theta_0 = 0°$ and 60°. A slope $\beta = 1.5$ that corresponds to the spectral exponent of a cloud optical depth model is added for convenience. **(b)** 1024x1024 pixels Landsat image from channel 4 (0.76-0.9 μm) taken on Sep. 24, 1997 over the ARM site in Oklahoma.

(2b) Intermediate scales. For these scales, we suggested a new approach that uses spectral contrast in the absorption properties of cloud liquid water. In analogy to the Normalized Difference Vegetation Index (NDVI), which is widely used by the land community for analyzing and compressing satellite data, we created a cloud index that we call a Normalized Difference for Nadir Radiances (NDNR). It is constructed from a combination of non-absorbing and absorbing wavelengths and has the potential of removing the radiative effect of cloud side illumination and shadowing at oblique solar angles.

Figure 3c illustrates how NDNR improves optical depth retrieval for the simulated marine Sc cloud field illuminated by the Sun at 60°. In contrast to a standard IPA, the normalized

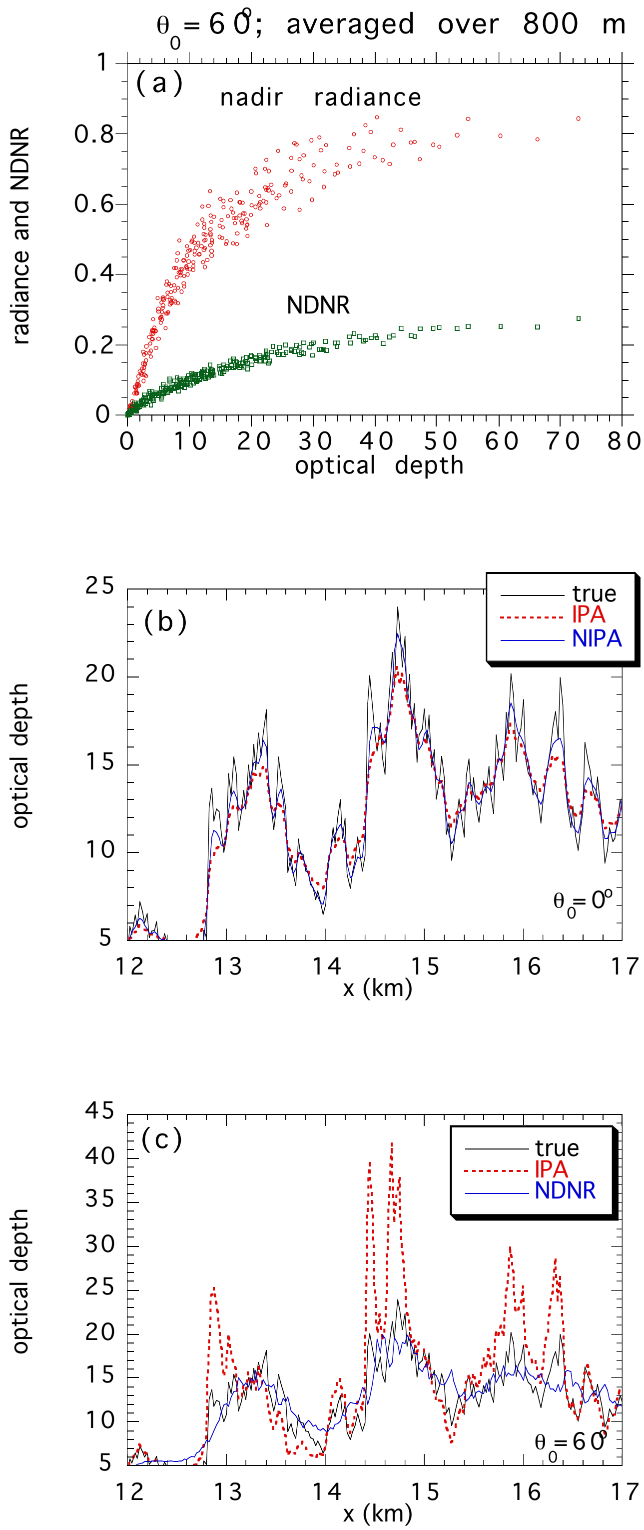

Figure 3: *Removal of 3D radiative effects*. **(a)** Averaged over 0.8 km nadir radiances and NDNR vs. cloud optical depth to be retrieved. **(b)** A 5 km fragment of the optical depth retrieved using a standard IPA and a newly developed NIPA. Solar zenith angle $\theta_0 = 0^o$. **(c)** A 5 km fragment of the optical depth retrieved using a standard IPA and a newly developed NDNR Solar zenith angle $\theta_0 = 60^o$. True optical depth is added for reference.

differences remove the effects of illuminated cloud edges as illustrated in Fig. 1a. Furthermore, averaging over 0.8 km (Fig. 3a) substantially improves the performance of NDNR, bringing it closer to a one-to-one relationship with cloud optical depth.

(3) Simulated satellite measurements

To validate the above technique, we computed and archived the Monte Carlo simulated nadir radiance fields for different underlying surfaces, illumination conditions, and stochastic models of cloud structure. To avoid realization-dependent conclusions, each cloud structure is represented by 10 realizations of a cloud model. In addition to conservative scattering channels, radiance fields for several channels with liquid water absorption have also been calculated.

All simulated data contains information about the spatial correlations that prevail in clouds. Because clouds cover a large range of scales from meters to kilometers, data analysis on a scale-by-scale basis has been performed in both Fourier and physical spaces.

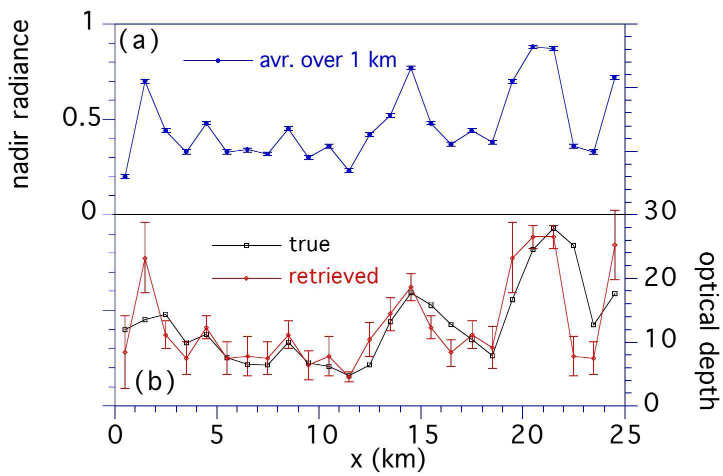

Figure 4: *Error bounds on the retrieved values of cloud optical depths.* **(a)** Averaged over 1 km nadir radiances with error bars equal to 0.01. Solar zenith angle $\theta_0 = 60^o$ (illumination from the left). **(b)** True and retrieved optical depths with error bounds of a one standard deviation.

(4) Error bounds on the inferred values of cloud optical depth

Figure 4 illustrates the preliminary results of the effects of cloud horizontal structure on the uncertainties of the retrieved cloud optical depths. The error bars for nadir radiances indicate the accuracy level of our "measurements" (Fig. 4a). Because of cloud inhomogeneity, these uncertainties are translated to a much larger errors in cloud optical depths inferred from the nadir radiances using an operational 1D retrieval. The error bars in Fig. 4b show a one standard deviation from the retrieved values of cloud optical depth. Comparing with true cloud optical depths, the retrieved values overestimate the illuminated part and underestimate shadows.

(5) Validation with ground-based measurements

Several comparisons between optical depths retrieved from Landsat scenes over the Oklahoma ARM site and from microwave radiometer data were performed. For retrieval, both a standard and advanced methods that include NIPA, NDNR and their combination, were used. The results are reported in Oreopoulos et al. (1999a,b).

Main scientific results to report

- We have developed a new method that restores the variability of the retrieved optical depth at small scales (Marshak et al., 1998a) and first applied it to overcast Landsat scenes (Oreopoulos et al., 1999a,b);
- We have shown that 3D cloud models resolved down to the mean-free-path (mfp) scale, with an incorrect assumption of homogeneity below that scale, are sufficient for estimating radiative properties averaged over mfp in both VIS and NIR spectral regions (Marshak et al., 1998b);
- We have developed a new approach to remove the effect of photon horizontal fluxes on cloud optical depth retrieval using a combination of radiances at nonabsorbing and absorbing wavelengths (Knyazikhin and Marshak, 1999; Oreopoulos et al., 1999a);
- We have related the accuracy of the standard IPA at absorbing wavelengths to the photon horizontal fluxes and a measurable radiative smoothing scale (Marshak et al., 1999c).

Some open problems we are working on

* Improving the new index NDNR to make it valid for all illumination conditions and different cloud types.

* Establishing a scale-dependent relationship between net horizontal fluxes and the error bounds on the inferred values of cloud optical depth.

* Developing a technique to estimate the magnitude of photon horizontal transport using scale-by-scale analysis of measured radiances at nonabsorbing and absorbing wavelengths.

* Evaluating the performance of the new algorithms using Landsat scenes over the Oklahoma’s ARM site and ground based microwave radiometer data.

* Testing and further improving the newly developed techniques using data from the MODIS Airborne Simulator (MAS), and, once they become available, real MODIS and ASTER data.

Project related publications (1998-1999)

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Marshak, A., L. Oreopoulos, A. Davis, W. Wiscombe, and R. Cahalan, 1999d: Accuracy of the Independent Pixel Approximation at absorbing wavelengths. In *Proceedings of 10th AMS Conference on Atmospheric Radiation*, 28 June – 2 July, 1999, Madison (WI), pp. @@–@@, Am. Met. Soc., Boston (Mass).

Oreopoulos, L., A. Marshak, R. Cahalan, and G. Wen, 1999c: Behavioral changes of observed and simulated cloud power spectra with solar zenith angle and wavelength: implications for cloud optical property retrievals. In *Proceedings of 10th AMS Conference on Atmospheric Radiation*, 28 June – 2 July, 1999, Madison (WI), pp. @@–@@, Am. Met. Soc., Boston (Mass).